

FIBER OPTICS FOR STRAIN MEASUREMENT AND ROBUST COMMUNICATIONS

Harold Kirkham and Larry Bergman
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, USA

INTRODUCTION AND BACKGROUND

Until recently, fiber optics tended to be regarded only as a medium for the transmission of large quantities of data. Work done in our laboratory has extended the application of fibers into a little-known area, the delivery of power. This paper shows how the optical delivery of power can be adapted to the measurement of strain and vibration. The approach can be used for large structures, and has advantages over conventional measurements. Costs are considered. In a separate development, a communication network designed to operate with arbitrary topology is described. Such a network could be used to acquire data from multiple locations even if it were partly damaged. This paper describes the network protocols that are needed.

In Part 1 of the paper we demonstrate that the optical power approach solves many of the problems associated with the measurement of strain. Strain is likely to be a useful measurement in the field of structure monitoring. In the second part of the paper we show that a robust communication network can be constructed to operate with arbitrary topology. Such a network gives the best hope of survival in the event of physical damage.

PART 1. STRAIN MEASUREMENT AND OPTICAL POWER DELIVERY

The robustness and familiarity of bonded wire gauges has made their continued use attractive. However, the signal from a strain gauge is very small, and the high gain needed to deal with such signals makes interference and common-mode effects problematical. An objective of our work was to combine a strain gauge with the noise immunity and signal transmission quality of optical fibers, and the flexibility and ease of use of microprocessors. The solution was to use an optically powered system, with the power supplied by a laser and delivered by a fiber.

The design of a sensor system can be optimized for the particular application. The use of a strain gauge in an optically powered measurement system of the type we have developed is limited by three considerations:

1. The strain gauge normally consumes more power than can readily be supplied by optical power. The electronics must therefore be de-energized between readings, to reduce power consumption.
2. The optically supplied system voltage may not be constant, and changes would contribute directly to measurement errors. The system must correct for this.
3. The signal level is too low to be digitized directly, and it must be amplified.

These problems are solved by the use of low-power amplifiers and by software in the microprocessor.

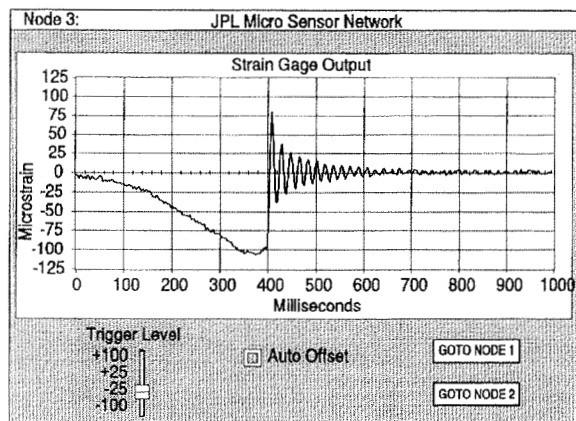
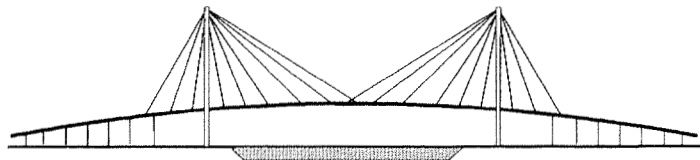


Figure 1. A prototype optically powered strain gauge system takes data 300 times per second, and returns the data to the base station in engineering units. It can be scaled and timed to suit the application simply by modifying scale factors in the software. Costs are moderate. For a typical node measuring (say) 4 strain gauges, the cost should be less than \$100.

Suppose it was desired to monitor the vibration performance of a bridge.

Figure 2. The *Pont de Normandie*, a cable-stayed design with a record main span 856 m long.



Before it was opened to the public, this bridge was tested in three ways (Petroski, 1995):

1. A static load was applied by having four traffic lanes occupied by fully loaded trucks parked nose to tail over 320 m of the main span.
2. A vertical load of 100 tonnes was applied and abruptly released, setting the bridge into vertical motion.
3. A lateral load of 80 tonnes was applied and suddenly released, setting up lateral vibrations.

While all this was going on, it may be presumed that strain was being monitored at various points on the bridge, including both the box-girder main span and the support cables. Measurement of the dynamic performance of the bridge could have been readily accomplished with the optically powered strain gauge system, even though the distances between measurement points might have been more than a km.

PART 2. AbNET, A ROBUST COMMUNICATION NETWORK

Introduction

In this part of the paper we discuss a fiber optic communication system originally designed for monitoring and control of electric power distribution systems. The power system requirements lead to a novel and widely applicable design because the assumptions that are usually made in designing general-purpose computer communication systems do not apply. The network protocols are quite unusual.

For routing our network uses a **flooding** algorithm. This is a distributed solution, all nodes being identical. At all nodes, any message received is retransmitted on all outgoing lines. By adopting such a strategy, a message inserted anywhere into the communications network will eventually be broadcast to all of the network. No message has any specific route; in fact all messages take all possible routes. Because of this, should any link in the network fail, there is still a chance that a copy of the packet may arrive at the destination through an alternate path. This redundancy provides reliability in AbNET.

The messages must be removed, too, to prevent endless circulation. The header of every message contains a unique identifying number that can be stored in every node that it passes through. Each node decides whether or not the message will be repeated depending on whether the message has been seen before. We refer to this as the “antibody” method, hence the name AbNET. The overhead required to implement this is small. One or two bytes, added to the message, suffice for message numbering.

Since most data acquisition schemes are hierarchical, with centralized acquisition and decentralized monitoring, AbNET can use a centralized polling strategy. A remote node is thus a “slave,” and can transmit only if so directed by the master node. There is no limit to the number of masters that can be used in a system, and borders can be dynamically reassigned to cope with network damage.

Services

A feature of a highly fault-tolerant network is that failure of any particular connection may not be detected, and several link failures may have occurred before there is a communication failure. AbNET addresses this by temporarily suspending the distributed flooding algorithm, and instead using a part of

the network layer that is designed specifically to have each node identify its nearest neighbor. The remote nodes build their own table of neighbors, which they send to the master periodically. Because the message flow required for this task resembles the operation of Sonar, we have designated this a Ping. In the prototype network, a ping operation takes place about every 10 seconds, and a table at the master station is updated at this frequency. The location of network damage can be mapped.

Reliability

For a packet transmission to fail in a typical AbNET network, it is necessary for transmissions on all links of a node to fail. Flooding ensures that it will be so long between dropped packets that causes other than bit error rate will predominate. The improvement due to the overconnected nature of the network is dramatic, and justifies the non-use of error-detection-based retransmission requests.

It is clear that the network is extremely robust if all the nodes are powered up. Power failure in part of the network is quite likely in the case of earthquake (which could black-out large areas), so that the provision of a backup battery is justified.

PART 3 CONCLUSIONS

A novel strain gauge system was described. By rapidly turning the electronics on and off, strain gauge measurements can be made with such low power consumption that it becomes possible to operate a local data system on the few mW of power that can be delivered optically, either by fiber or by a solar cell. The resulting node can be optically isolated, and suffers no common mode or interference problems. The local microprocessor can perform periodic calibration checks.

The design of a fiber optic communication network for monitoring and control in power distribution systems has been discussed. By appropriate choice of protocols, a fault-tolerant system that operates in any arbitrary network configuration has been devised.

The network, called AbNET, is a packet-based distributed protocol system. Flooding is used for maximum failure tolerance. Hierarchical (master-slave) polling controls access to the system. This supports many data acquisition and control applications. The protocols allow multiple adjacent masters to share resources. A low-level network service reports the network's configuration to the master, where changes can be logged, and action taken if needed.

BIBLIOGRAPHY/REFERENCES

- Kirkham, H. and Johnston, A.R., *Electric and Magnetic Field Meters Developed for the U.S. Department of Energy*, JPL Publication 88-1, 1988, Jet Propulsion Laboratory, Pasadena, California.
- Kirkham, H., Johnston, A.R., Jackson, S.P. and Sheu, K., *AC and DC Electric Field Meters Developed for the U.S. Department of Energy*, JPL Publication 87-20, 1987, Jet Propulsion Laboratory, Pasadena, California.
- Perlman, R.; (1983 December), *Fault-Tolerant Broadcast of Routing Information*, Computer Networks, pp. 395-405.
- Petitpierre, C., (1984, August), *Meshed Local Computer Networks*, IEEE Communications Magazine, Vol 22, No 8, pp. 36-40.
- Petroski, H., *Le Pont de Normandie*, American Scientist, September-October 1995, pp. 415-419.
- Zimmermann, H., (1980, April), *OSI Reference Model—the ISO Model of Architecture for Open Systems Interconnection*. IEEE Transactions on Communications, Volume COM-28, No. 4, pp. 425-432.

Acknowledgements

Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy, Office of Energy Management Systems, Utility Systems Division, through an agreement with the National Aeronautics and Space Administration.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, product, or process disclosed, or represents that its use would not infringe privately owned rights.